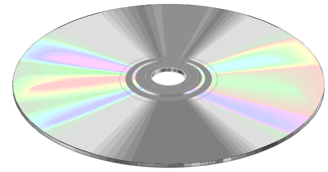
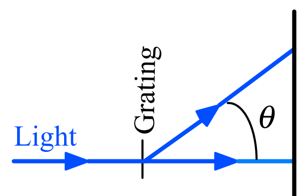
Diffraction Gratings



Introduction: A *diffraction grating* consists of a large number of equally spaced parallel "slits" or sources of diffracted light. When light is incident on a grating, the light from each "slit" diffracts then interferes with the light from the other "slits." When the conditions for constructive interference for a given wavelength are satisfied, that color is enhanced and hence observed. For example, this phenomenon is responsible for the colors that are observed in white light reflected from a CD i.e. a CD behaves as a *reflection* grating. CDs are made to reflect light because that is the way that they are read. Next, a CD has a spiral, grooved track (usually composed of pits) and thus, for a small region on the surface of a CD, the grooves create an approximately parallel pattern. Consequently, the light reflected from a small portion of the surface diffracts as approximately parallel sources. Additional discussion of CDs will be given later in this write-up. It is also straightforward to construct *transmission* gratings where the interference occurs for transmitted light. A CD will act as a transmission grating if the reflective coating is removed. In this lab we will first establish the properties of a laboratory transmission grating. We will then show that a CD behaves similarly both in transmission and reflection and we will make measurements to determine the distance between the grooves. Next, we will use the laboratory transmission grating to analyze the light emitted by hydrogen atoms and we will compare the results with the predictions of theory. Finally, we will study the light emitted by helium atoms and a "typical" light bulb.



Theory: As discussed in section 36.7 of the textbook, if light of wavelength λ is incident on a grating along the perpendicular to the surface of the grating and is observed at an angle θ relative to the perpendicular, constructive interference occurs when

[Text eq. 36.13] $$\sin\theta = \frac{m\lambda}{d} \quad (m = 0, \pm1, \pm2, \pm3, \ldots) \qquad (1)$$

d is the distance between the slits in the diffraction grating and m is an integer called the order of the pattern.

Note: Eq. (1) is slightly different than eq. (36-13) in the text in that negative values of m are included. This accounts for the fact that θ can be both positive and negative i.e. the pattern is usually symmetrical about the middle, $\theta = 0$. The situation is shown in the next figure.

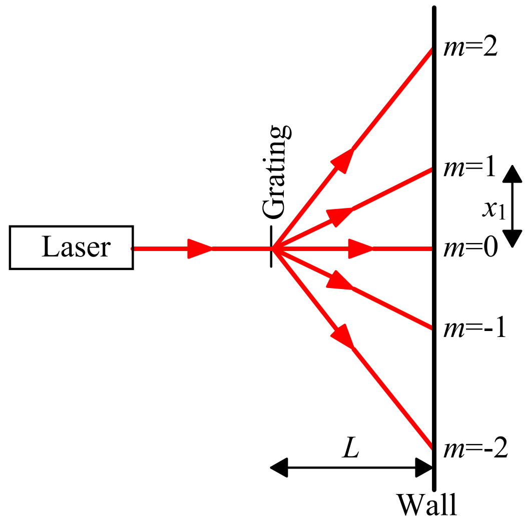
If light of a known wavelength is incident on a grating, d can be determined from measurements of the angles where bright light is observed. Conversely, if a grating of known value of d is used, the wavelengths of the light can be determined from measured angles. We will use both approaches in this lab.

Laboratory Transmission Diffraction Grating Our first experiment is to determine the value of d for our laboratory transmission diffraction grating. We will consider the wavelength of the dominant, red light from a helium-neon laser to be known. That value is $\lambda_{\text{He-Ne}} = 632.8$ nm.

Note: Do not let the laser beam shine into your eye i.e. do not look into the laser.

Procedure

1. Set up the equipment as shown in the next "top view" sketch. The grating should be at the end of the table and the laser should shine through it so that spots are created on the wall. The laser beam should be perpendicular both to the diffraction grating and to the wall. The best test of this is if the pattern on the wall is symmetrical i.e. the same to the left and to the right.



2. Measure the distance from the grating to the wall and record the value as $L_{\text{Grating-Wall}}$ in the space provided.

R1: $L_{\text{Grating-Wall}}$ = _________ ± _________ m

3. Measure the distances from the center spot to the other spots (positions of constructive interference). R2: Record the values as x_m in the table. (x_1 is shown in the diagram.)

4. Use the values of x_m and L to calculate the values of θ. R3: Record the values of θ in the table.

R4: Show a sample calculation of θ.

m	x_m (m)	θ (°)	d_{Grating} (m)
+1			
-1			
+2			
-2			

R5: Explain why third order constructive interference ($m = \pm 3$) is not included in the table.

5. Use eq. (1) to calculate the value of d_{Grating} for each angle. R6: Record the values in the table.

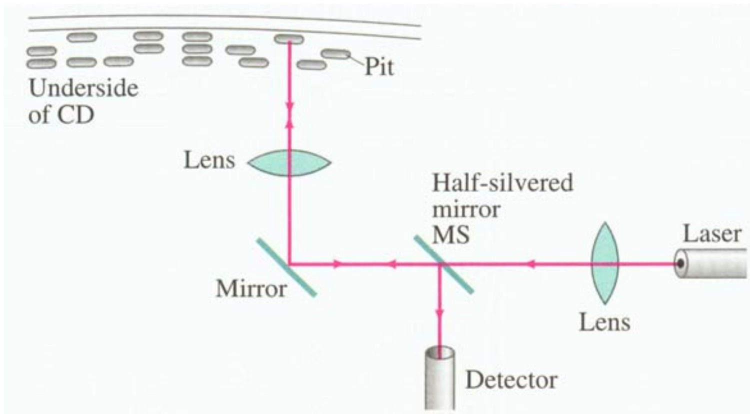
6. Decide on your best value of d (average value, etc.) and record it as $d_{\text{Grating,best}}$ in the space provided.

R7: $d_{\text{Grating,best}}$ = _________ ± _________ m R8: $d_{\text{Grating,accepted}}$ = _________ ± _________ m

7. There may be an accepted value of d (or $1/d$) written on the grating. If there is an accepted

value, record the value as $d_{\text{Grating,accepted}}$ in the space provided.

Compact Discs The next sketch and following simplified explanation of the operation of a CD are taken from the extended version of our textbook, *Physics*, D. C. Giancoli, Prentice Hall, New Jersey, 2000, page 1022. "The fine beam of a laser, focused even more finely with lenses, is directed at the undersurface of a rotating compact disc. The beam is reflected back from the areas between pits but reflects much less from pits. The reflected light is detected as shown, reflected by a half-reflecting mirror MS. The strong and weak reflections correspond to the 0s and 1s of the binary code representing the audio or video signal." (Interesting additions to this discussion are that the pit depths are chosen to give destructive interference thereby enhancing the weak reflections and there is a diffracting grating in the laser beam path where the diffracted light is used to track the spiral groove.)



The parallel arrangement of the pits, mentioned in the **Introduction** to this write-up, should be apparent from the sketch. The regions between the approximately parallel pits give rise to the approximately parallel sources of diffracted light that enable typical CDs to act as reflection gratings. However, a manufacturer of CDs (Dering Corporation, Lancaster, PA) has been kind enough to supply us with CDs that not "mirrored" yet still contain digital information (the pits). (Such incomplete CDs are sometimes used as packaging for CD-RWs.) Our second experiment will be to use one of those as a transmission grating to determine the spacing between the rows of pits. Our third experiment will be to verify that a standard, reflecting CD can act as a diffracting grating.

Procedure - Transmission

Note: The CD is not as efficient as the laboratory grating so the spots (positions of constructive interference) produced by the grating will be weak.

1. Replace the laboratory transmission grating with a transparent CD (or half of a transparent CD).

2. Shine the light through the top of the CD then through the left or right side of the CD.

R9: Give a qualitative explanation of the results. Be sure to explain which way the light diffracts (spreads) relative to the orientation of the "grooves." Does the diffraction pattern occur parallel or perpendicular to the "grooves?"

3. Attempt to make the laser beam perpendicular to both the CD and the wall. Measure the

distance from the CD to the wall and record the value in the space provided.

R10: $L_{\text{CD-Wall}}$ = ________ ± ________ m

4. Measure the distance from the center spot to each first order diffraction maximum. R11: Record each value as x_m in the table.

m	x_m (m)	θ (°)	d_{CD} (m)
+1			
-1			

5. Use the values of x_m and L to calculate the values of θ. R12: Record the values of θ in the table.

6. Calculate d_{CD}. R13: Record the values of d_{CD} in the table.

R14: How do the values of d_{CD} compare with $d_{Grating}$ i.e. is the spacing of the grooves on the CD larger or smaller than for the laboratory grating?

Our goal for the third experiment is to study the interference pattern from a standard CD.

Procedure – Reflection

1. Rotate the laser by 180^{o} so that if the beam reflects from a mirror it will strike the wall.

2. Position a standard CD so that it will reflect the laser beam onto the wall.

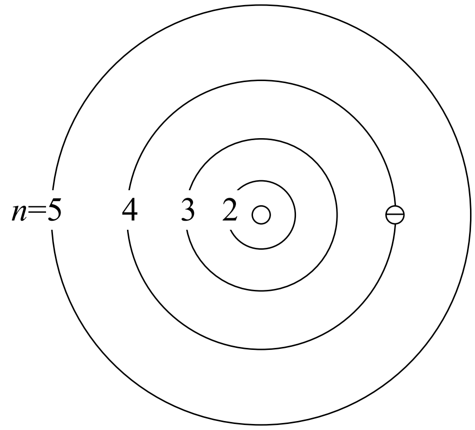
R15: Describe the results qualitatively.

Hydrogen The fourth experiment is to determine the wavelengths of (visible) light emitted from a hydrogen atom.

Theory A semi-classical theory, the Bohr model of hydrogen is given in section 38-10 of our textbook. In that theory, hydrogen is comprised of an electron circulating in orbit around a proton. As you may have heard, only certain orbits are allowed. The lowest energy state (orbit) of the electron is characterized by n = 1 and the orbit has a radius of

[Text eq. 38-12b] $$r_1 = 0.529\text{x}10^{-10} \text{ m.} \qquad (2)$$

Higher energy states of the electron are characterized by $n = 2,3,\ldots$ and the radii are $r_n = n^2 r_1$. An electron circulating in the $n = 4$ orbit is shown in the next diagram.

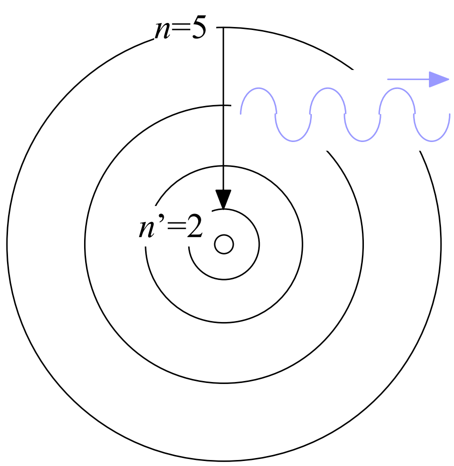


Further, if an electron transitions from a high energy level to a low energy level, the atom must give off energy. If the change in energy of the electron is in a special range, that energy takes the form of visible light. The Bohr theory enables us to predict the wavelengths of the light that are emitted from the hydrogen atom. For us, the important result of the theory is that for a one-electron atom (or one-electron ion) the wavelengths are given by

[Text eq. 38-14] $$\frac{1}{\lambda} = \frac{Z^2 e^4 m}{8\epsilon_o^2 h^3 c}\left(\frac{1}{(n')^2} - \frac{1}{(n)^2}\right) \qquad (3)$$

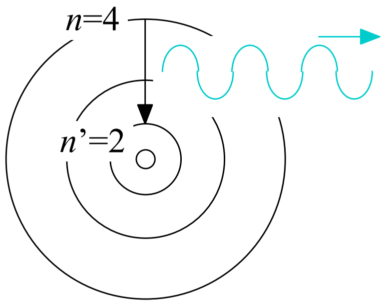
In eq. (3), n designates the orbit for the higher (initial) energy level of the electron and n' is the value for the lower (final) energy level. Z is the number of protons in the nucleus so for our experiment $Z = 1$ since we will be studying hydrogen. The only parameter in eq. (3) that we have not studied this semester is Planck's constant, h. Planck's constant is a "universal" constant that is very important in modern physics. The point of all this is to show that the wavelengths of the light emitted from a hydrogen atom can be predicted using many of the quantities that we have been learning about this semester such as ϵ_o, m (the mass of the electron), e (the charge on the electron) and c (the speed of light). This was a very important achievement of physics when it was formulated in 1913.

We will now use eq. (3) to predict the wavelengths of the light that should be emitted from hydrogen atoms. For each of the transitions shown below, calculate the predicted wavelength of light and record each result in the space provided. Show your calculation of the wavelength of light emitted because of the $n = 5$ to $n = 2$ transition.

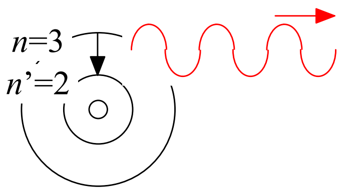


R16: λ_{52} = __________ nm

R17: Calculation



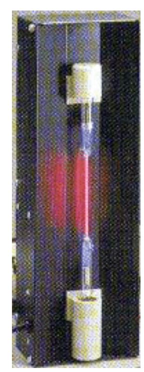
R18: λ_{42} = __________ nm



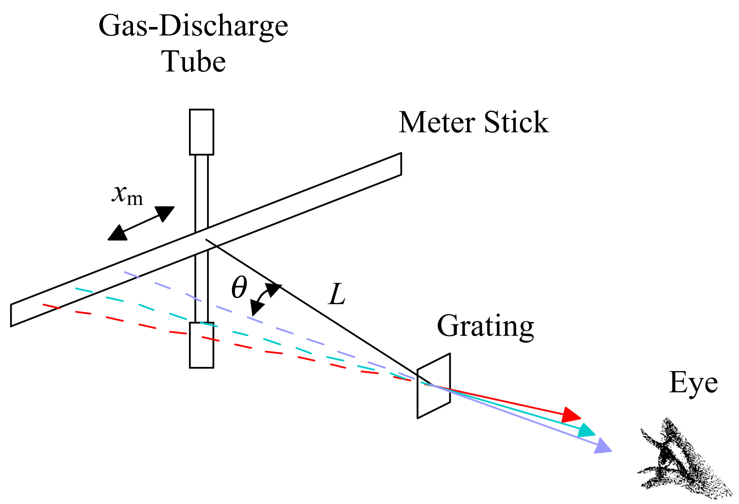
R19: λ_{32} = ___________ nm

We will now attempt to observe this light and measure the wavelengths in order to verify the predictions of the Bohr model.

Experiment (Textbook Section 38-9) The hydrogen is contained inside a glass tube with an electrode in each end. As discussed in the textbook on page 963, this is referred to as a gas-discharge tube. A typical tube (and enclosure) is shown at the right and in the textbook. When a voltage (The tube operates at about 5000 V.) is applied across the electrodes (top and bottom of the tube), the hydrogen atoms inside the tube emit light. The reason that they emit light is that free electrons in the tube acquire kinetic energy because of the voltage. (The free electrons are accelerated by the corresponding electric field responsible for the voltage.) Those electrons collide with atoms and transfer some or all of their kinetic energy to the hydrogen atoms so that electrons are either raised to higher energy levels (excited states) or become free. That the voltage (5000 V) is high enough may be obvious from the fact that the ionization energy of hydrogen is 13.6 eV. This implies that if an electron moves freely through a voltage of about 13.6 V, it can gain enough kinetic energy to eject an electron from an atom. Consequently, because of the voltage, there is enough energy available to place atoms into all possible energy levels. Visible light is emitted when the electrons with $n \geq 3$ transition to $n' = 2$.



We can use the laboratory transmission grating to separate light into the individual wavelengths (colors), called the spectrum. This is, of course, based on eq. (1) since for a fixed slit width (d), constructive interference occurs at different angles (θ) for different wavelengths (λ). The easiest way for us to do this experiment is shown in the next diagram.



1. Set up the meter stick, hydrogen gas-discharge tube and grating as shown.

2. Turn on the tube and observe the hydrogen spectrum. Only the three most prominent (longest) wavelengths of light from the hydrogen atom are shown in the diagram. To be consistent with our textbook they are referred to as red, blue-green and blue. However, the blue line is more properly referred to as violet. The reason that it should be referred to as violet will be apparent from the spectrum.

3. Measure the distance from the grating to the meter stick and record the value in the space provided.

R20: $L_{\text{Grating-Meter Stick}}$ = ________ ± ________ m

4. Measure the values of x_{m} for the various colors. R21: Record the values of x_{m} in the next table.

5. Use the values of x_{m} and $L_{\text{Grating-Meter Stick}}$ to calculate the values of θ. R22: Record the values of θ in the table.

6. If a value of $d_{Grating,accepted}$ is available (page 2), use it and the results in the table and eq. (1) to calculate the observed wavelengths, $\lambda_{\text{experimental}}$. If a value of $d_{Grating,accepted}$ is not available, use $d_{Grating,best}$ in the calculations. R23: Record the values of $\lambda_{\text{experimental}}$ in the next table.

R24: Show a sample calculation of $\lambda_{\text{experimental}}$.

Color	m	x_m (m)	θ (°)	$\lambda_{experimental}$ (nm)	$\lambda_{textbook}$ (nm)
Red	+1				
Red	-1				
Blue-Green	+1				
Blue-Green	-1				
Blue (Violet)	+1				
Blue (Violet)	-1				

R25: "Accepted" values are listed in the textbook in Figure 38-20 on page 964. Record those values in the last column of the table.

R26: Compare the experimental, theoretical and textbook values of the wavelengths associated with the hydrogen spectrum.

Note: While the Bohr model predicts the wavelengths of the light emitted from hydrogen very well, almost everything else about the theory is wrong i.e. does not agree with experiment. Not long after the Bohr model, the Schroedinger wave equation was developed and it correctly describes many more features of the hydrogen atom. Interestingly, even though the Schroedinger wave equation is much more sophisticated, the predictions for the wavelengths of light are the same as for the Bohr model. Should you wish to learn more about these and other aspects of modern physics (theory of relativity, etc.) take SP 301.

7. The same three lines (red, blue-green and blue) should be observable in the second order hydrogen spectrum should be easily observable.

R27: Are those lines observable in second order? Discuss.

8. As regards third order, if you don't look carefully, the blue line appears to be missing. This is an accident. To understand the reason for this, calculate the angle where the third order blue line should appear and calculate the angle where the second order red line should appear. Record both values in the space provided.

R28: $\theta_{\text{third order blue}}$ = _________ ± _________ °   R29: $\theta_{\text{second order red}}$ = _________ ± _________ °

R30: Discuss how these calculations explain why it is difficult to observe the blue line for the third order hydrogen spectrum.

Helium As the fifth experiment, replace the hydrogen tube with a helium tube and use the diffraction grating to observe the new spectrum.

R31: Give a qualitative description of the helium spectrum.

Incandescent Light As the sixth experiment, replace the gas discharge tube with an incandescent light and use the diffraction grating to observe the new spectrum.

R32: Give a qualitative description of the spectrum caused by the incandescent light.

End of Lab Checkout Tidy the workstation.